# Robust Exploration and Commercial Missions to the Moon Using NTR / LANTR Propulsion and Lunar-Derived Propellants

Stanley K. Borowski[1], Stephen W. Ryan[1], Laura M. Burke[1], David R. McCurdy[2], James E. Fittje[2], and Claude R. Joyner[3]

*[1]NASA Glenn Research Center, Cleveland, OH 44135*
*[2]Vantage Partners, LLC at Glenn Research Center, Brook Park, OH 44142*
*[3]Aerojet Rocketdyne, West Palm Beach, FL 33410*
*telephone: (216) 977-7091, email: Stanley.K.Borowski@nasa.gov*

**Abstract.** The nuclear thermal rocket (NTR) has frequently been identified as a key space asset required for the human exploration of Mars. This proven technology can also provide the affordable "access through cislunar space" necessary for commercial development and sustained human presence on the Moon. In his "post-Apollo" Integrated Space Program Plan (1970–1990), Wernher von Braun, proposed a reusable nuclear thermal propulsion stage (NTPS) to deliver cargo and crew to the Moon to establish a lunar base before undertaking human missions to Mars. The NTR option was selected by von Braun because it was a demonstrated technology capable of generating both high thrust and high specific impulse ($I_{sp}$ ~900 s) – twice that of today's best chemical rockets. In NASA's Mars Design Reference Architecture (DRA) 5.0 study, the crewed Mars transfer vehicle used three 25 $klb_f$ "Pewee" engines – the smallest and highest performing engine tested in the Rover program – along with graphite composite fuel. Smaller lunar transfer vehicles – consisting of a NTPS using three ~16.5 $klb_f$ "Small Nuclear Rocket Engines (SNREs)", an in-line propellant tank, plus the payload – can enable a variety of reusable lunar missions. These include cargo delivery and crewed lunar landing missions. Even weeklong "tourism" missions carrying passengers into lunar orbit for a day of sightseeing and picture taking are possible. The NTR can play an important role in the next phase of lunar exploration and development by providing an affordable in-space lunar transportation system (LTS) that can allow initial outposts to evolve into settlements supported by a variety of commercial activities such as in-situ propellant production used to supply strategically located propellant depots and transportation nodes. The utilization of iron-oxide (FeO)-rich volcanic glass or lunar polar ice (LPI) deposits (each estimated at billions of metric tons) for propellant production can reduce the launch mass requirements from Earth and can enable reusable, surface-based lunar landing vehicles (LLVs) using liquid oxygen/hydrogen ($LO_2$/$LH_2$) chemical rocket engines. Afterwards, $LO_2$/$LH_2$ propellant depots can be established in lunar equatorial and polar orbits to supply the LTS. At this point a modified version of the conventional NTR – called the $LO_2$-augmented NTR, or LANTR – would be introduced into the LTS allowing bipropellant operation and leveraging the mission benefits of refueling with lunar-derived propellants for Earth return. The bipropellant LANTR engine utilizes the large divergent section of its nozzle as an "afterburner" into which oxygen is injected and supersonically combusted with nuclear preheated hydrogen emerging from the engine's choked sonic throat—essentially "scramjet propulsion in reverse." By varying the oxygen-to-hydrogen mixture ratio, LANTR engines can operate over a range of thrust and $I_{sp}$ values while the reactor core power level remains relatively constant. Eventually, a LANTR-based LTS can enable a rapid "commuter" shuttle with "one-way" trip times to and from the Moon on the order of 36 hours or less. Even if only 1% of the extracted propellant from identified volcanic glass and polar ice deposits were available for use in lunar orbit, such a supply could support daily commuter flights to the Moon for many thousands of years! An evolutionary mission architecture is outlined and a variety of lunar missions and transfer vehicle designs are examined, along with the increasing demands on propellant production as mission complexity increases. A comparison of vehicle features and engine operating characteristics, for both NTR and LANTR engines, is also provided along with a brief discussion on the propellant production issues associated with using volcanic glass and LPI as source material.

**Keywords:** NTR, LANTR, Lunar-Derived Propellant

# INTRODUCTION AND BACKGROUND

Today there is considerable discussion within NASA, the Congress and industry regarding the future direction and focus of the United States' human space program. According to NASA, the direction and focus is a "Journey to Mars" [1] sometime around the mid-to-late 2030's. While NASA's sights are set on Mars, there is another destination of greater interest to the worldwide space community – the Moon. Located just 3 days from Earth, the Moon is an entire world awaiting exploration, future settlement and potential commercialization. It has abundant resources and is an ideal location to test and demonstrate key technologies and systems (e.g., surface habitation, long-range pressurized rovers, surface power and resource extraction systems) that will allow people to explore, work, and live self-sufficiently on another planetary surface. Lunar missions also provide a unique proving ground to demonstrate another important in-space technology – Nuclear Thermal Propulsion (NTP). Essential for human missions to Mars, high performance NTP can play an important role in *"returning humans to the Moon to stay"* by providing an affordable in-space LTS that can allow initial lunar outposts to evolve into permanent settlements engaged in and supported by a variety of commercial activities [2,3].

Despite NASA's "been there, done that" attitude towards the Moon, a human lunar return mission has a strong appeal to many others who would like to see humans again walk on its surface and to whom the Apollo program has become a distant memory. Plans for human surface missions and settlements on the Moon in the 2025 – 2030 timeframe are being openly discussed by Europe, China, and Russia [4,5,6]. A number of private companies in the United States – Bigelow Aerospace [7], Shackleton Energy Company (SEC) [8], and most recently, the United Launch Alliance (ULA) in their "Cislunar-1000" plan [9] – are also discussing possible commercial ventures to the Moon during this same time period.

Lunar-derived propellant (LDP) production – specifically lunar-derived liquid oxygen ($LLO_2$) and liquid hydrogen ($LLH_2$) – offers significant mission leverage and are central themes of both SEC's and ULA's plans for commercial lunar development. Samples returned from different sites on the Moon during the Apollo missions have shown that the lunar regolith has a significant oxygen content. Discovered on the final Apollo (17) mission, FeO-rich volcanic glass beads have turned out to be a particularly attractive source material for oxygen extraction [10]. Subsequent lunar probe missions have provided data indicating the possible existence of large quantities of water ice trapped in deep, permanently shadowed craters located at the Moon's poles [11]. If this resource is accessible and can be extracted economically, then it would provide a valuable source of both $LLO_2$ and $LLH_2$.

Besides LDPs, an efficient, proven propulsion technology with reuse potential is also important to ensure affordable "access through cislunar space." The NTR is that technology. It generates both high thrust and high specific impulse ($I_{sp}$ ~900 s) – twice that of today's highest performing $LO_2/LH_2$ chemical rockets – but it is essentially a mono-propellant engine using only $LH_2$ to maintain the reactor fuel elements at their required operating temperature. The heated hydrogen gas exiting the reactor is then exhausted out the engine's nozzle to generate thrust. A key question then is *How can the high performance of the NTR and the leverage potential of LDP best be exploited?* The answer is *the "$LO_2$-Augmented" NTR (or LANTR) – a $LH_2$-cooled NTR outfitted with an $O_2$ "afterburner nozzle" and feed system* [12,13,14]. LANTR combines NTR and supersonic combustion ramjet engine technologies. The result is a versatile high performance engine that allows "bipropellant" operation and a robust nuclear LTS with unique capabilities that can take full advantage of the mission leverage provided by using LDPs.

In light of the current interest in LDPs [8,9,15], and as part of its ongoing efforts to quantify the benefits of using NTP for future lunar missions, GRC has been examining the unique mission capabilities that may be possible by infusing LANTR propulsion into a nuclear-powered LTS that utilizes LDPs. This paper provides a brief summary of our initial analysis results to date and touches on the following topics. First, the benefits and options for using LDPs are discussed along with the production issues associated with using volcanic glass and LPI as source material. Next, a system description of the NTR and the LANTR concept are presented along with performance projections for the engine as a function of the oxygen-to-hydrogen (O/H) mixture ratio (MR) used in the afterburner nozzle. An evolutionary mission architecture with assumptions is then outlined and the benefits of using LDP in terms of reduced vehicle size, launch mass and engine burn time are quantified. A sampling of different missions, lunar transfer vehicle (LTV) types, and transit times is then presented, along with the associated LDP refueling needs as the mission complexity and $\Delta V$ requirements increase.

## BENEFITS AND OPTIONS FOR USING LUNAR-DERIVED PROPELLANTS

Previous studies conducted by NASA and its contractors [16,17] have indicated a substantial benefit from using lunar-derived propellants – specifically $LLO_2$ in the lunar space transportation system. In a LTS using $LO_2/LH_2$ chemical rockets, ~6 kilograms (kg) of mass in low Earth orbit (LEO) is required to place 1 kg of payload on the lunar surface (LS). Of this 6 kg, ~70% (4.2 kg) is propellant and ~85.7% of this mass (3.6 kg) is oxygen assuming the engines operate with an O/H MR of 6:1. Since the cost of placing a kilogram of mass on the LS is ~6 times the cost of delivering it to LEO [18], the ability to produce and utilize $LLO_2$ from processed lunar regolith, or $LLO_2$ and $LLH_2$ from the electrolysis of LPI deposits, can provide a significant mission benefit. Providing $LLO_2$ and $LLH_2$ for use in fuel cells, life support systems and the chemical rocket engines used on LLVs, allows "higher value" cargo (people, manufacturing and scientific equipment, etc.) to be transported to LEO and on to the Moon instead of bulk propellant mass.

Samples brought back on the Apollo missions have shown that oxygen is abundant in the lunar regolith (~43% by mass) and can be extracted from the mineral "ilmenite ($FeOTiO_2$)" or from "FeO-rich" orange and black volcanic glass beads, discovered on the Apollo 17 mission to Taurus-Littrow [19], using the hydrogen reduction process. The process produces water that is then electrolyzed to obtain oxygen and hydrogen – a portion of which is recycled back as the catalyst. Reduction experiments conducted at the Johnson Space Center [20,10] have shown the glassy (orange) and crystalline (black) beads to be an attractive feedstock producing oxygen yields up to 4.7wt%. They are fine grained (see Figure 1) and can be fed directly into a $LLO_2$ production plant with little or no processing prior to reduction. More importantly, vast deposits of these volcanic glass beads have been identified at a number of candidate sites on the lunar nearside including Mare Serenitatis (close to the Taurus-Littrow landing site), Mare Vaporum, Rima Bode, and Sinus Aestuum [21]. At the southeastern edge of Mare Serenitatis alone, it is estimated the existing pyroclastic deposits could produce well in excess of 2 billion metric tons (t; 1 t =1000 kg) of $LLO_2$. The estimated total power (in $kW_e$) to produce $LLO_2$ from volcanic glass is ~21 x $LLO_2$ production rate (in kg/hr) [12].

Recently, the Clementine, Lunar Prospector [11], and Chandrayaan-1 [22] lunar probe missions have provided data indicating the possible existence of large quantities of water ice (estimated at 100's of millions to billions of metric tons) trapped in deep, permanently shadowed craters located at the Moon's poles (shown in Figure 1). Lunar polar ice deposits are important because the recovered water can supply both oxygen and hydrogen (at a ratio of 8:1), assuming the deposits can be economically accessed, mined, processed and stored for their desired use.

Higher $\Delta V$ budgets are required to access lunar polar orbit (LPO) sites and the candidate craters are deep and extremely cold (~50 K / -370 F) posing major challenges for mining and processing these cold ice-bearing materials [23]. Concepts have been proposed to excavate and extract LPI-derived water [24] a portion of which would be electrolyzed on the Moon to supply ascent/descent propellant to "water tanker" LLVs that would deliver the remaining water resource to an orbiting propellant depot for electrolysis and storage there. The required electrolysis cell input power (in $kW_e$) is ~4.9 x $H_2O$ electrolysis rate (in kg/hr). The quantities of LDPs needed and the total power requirements (for mining, $H_2O$ separation and electrolysis) will depend on the mission type and frequency.

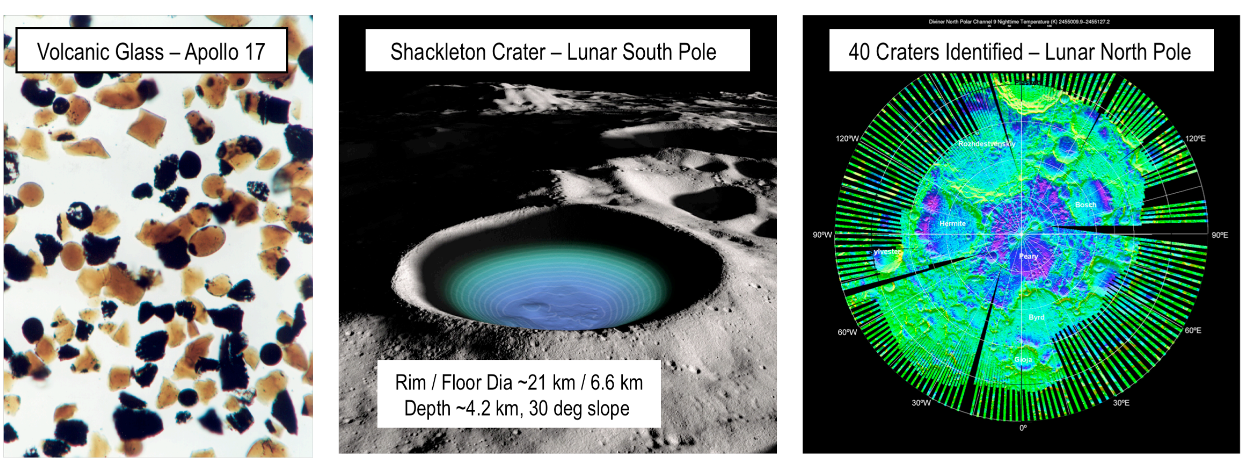


**FIGURE 1.** Volcanic Glass Feedstock and Candidate Craters for LPI Deposits at the Lunar South and North Poles

## NTR / LANTR SYSTEM DESCRIPTION AND PERFORMANCE CHARACTERISTICS

The NTR uses a compact fission reactor core containing “enriched” uranium (U)-235 fuel to generate 100’s of megawatts of thermal power ($MW_t$) required to heat the $LH_2$ propellant to high exhaust temperatures for rocket thrust [25]. In an “expander cycle” engine (Figure 2), high pressure $LH_2$ flowing from a turbopump assembly (TPA) is split into two paths with the first cooling the engine’s nozzle, pressure vessel, neutron reflector, and control drums, and the second path cooling the engine’s core support tie-tube assemblies. The flows are then merged and the heated $H_2$ gas is used to drive the TPAs. The hydrogen turbine exhaust is then routed back into the reactor pressure vessel and through the internal radiation shield and upper core support plate before entering the coolant channels in the reactor’s fuel elements. Here it absorbs energy produced from the fission of U-235 atoms, is superheated to high exhaust temperatures ($T_{ex}$ ~2700 K or more depending on the uranium fuel loading), then expanded out a high area ratio nozzle (~300:1) for thrust generation. Multiple control drums, located in the reflector region surrounding the reactor core, regulate the neutron population and reactor power level over the NTR’s operational lifetime.

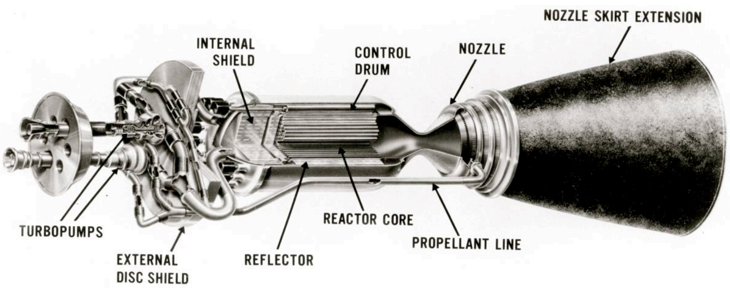


**FIGURE 2.** Schematic of “Expander Cycle” NTR Engine with Dual $LH_2$ Turbopumps

Recent studies showing the benefits of NTP for a variety of exploration and commercial lunar missions [2,3] have used a “common” NTPS employing a 3-engine cluster of SNREs. Each SNRE has a power output of ~365 $MW_t$ and produces ~16.5 $klb_f$ of thrust. Its graphite composite fuel operates at a peak temperature of ~2860 K and the corresponding hydrogen exhaust temperature is ~2734 K. With a chamber pressure of 1000 psia, a hydrogen flow rate of ~8.30 kg/s and a nozzle area ratio (NAR) of ~300:1, the engine’s $I_{sp}$ is ~900 s. The total engine length and nozzle exit diameter are ~5.8 m and ~1.53 m, respectively, and the engine’s thrust-to-weight ratio is ~3.02. Additional reactor and engine parameters for the updated SNRE are found in Reference [3].

In order to take full advantage of available LDPs, each SNRE is outfitted with an $O_2$ “afterburner” nozzle containing the $O_2$ injectors and an $O_2$ feed system. The oxygen is stored as a cryogenic liquid at low pressure and must be pressurized and gasified prior to its injection into the nozzle. This is accomplished by diverting a small fraction of the engine’s hydrogen flow (~3%) to an oxidizer-rich gas generator that drives a $LO_2$ TPA used to deliver the gasified $LO_2$ to injectors positioned inside the afterburner nozzle downstream of the throat [13,14]. Here it mixes with the hot $H_2$ and undergoes supersonic combustion adding both mass and chemical energy to the rocket exhaust. Transitioning to “LANTR mode” operation has many advantages. It provides a variable thrust and $I_{sp}$ capability (shown in Table 1), shortens engine burn times, extends engine life and allows bipropellant operation.

**TABLE 1.** SNRE / LANTR Performance Characteristics as a Function of O/H Mixture Ratio

| O/H Mixture Ratio | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Delivered $I_{sp}$ (s) | 900** | 725 | 637 | 588 | 552 | 516 |
| Thrust Augmentation Factor | 1.0 | 1.611 | 2.123 | 2.616 | 3.066 | 3.441 |
| Thrust ($lb_f$) | 16,500 | 26,587 | 35,026 | 43,165 | 50,587 | 56,779 |
| Engine Mass ($lb_m$) | 5,462 | 5,677 | 5,834 | 5,987 | 6,139 | 6,295 |
| Engine T/W | 3.02 | 4.68 | 6.00 | 7.21 | 8.24 | 9.02 |

** Fuel Exit / Hydrogen Exhaust Temperature = 2734 K, Chamber Pressure = 1000 psia and NAR = 300 to 1

## EVOLUTIONARY NUCLEAR LTS ARCHITECTURE AND RESULTS

The enhanced mission capability resulting from the combined use of LANTR propulsion and $LLO_2$ was quantified and reported on [12] by GRC more than 20 years ago. At that time the primary LDP and source material considered was $LLO_2$ and volcanic glass, and only Earth-supplied $LH_2$ was used. An evolutionary LTS was analyzed focused on using high performance NTP to maximize delivered surface payload (PL) on each mission. The increased PL was dedicated to installing modular $LLO_2$ production units with the intent of supplying $LLO_2$ to surfaced-based LLVs initially, then to the in-space LTVs at the earliest possible opportunity. This assessment re-examines this evolutionary nuclear LTS architecture and expands it to also include the use of LPI as the source material.

Figure 3 shows the variation in LTV size, initial mass in low Earth orbit (IMLEO), increased mission capability and engine burn time resulting from the development and utilization of $LLO_2$. Figure 3a shows a fully reusable nuclear LTV (NLTV) for a crewed lunar landing mission that departs from LEO (407 km) and captures into a 300 km altitude equatorial low lunar orbit (LLO). The NLTV consists of three elements: (1) a common NTPS with three SNRE-class engines; (2) an in-line $LH_2$ tank; and (3) the PL element. The NTPS and in-line element use a common propellant tank (~15.7 m in length) that carries ~39.7 t of $LH_2$. The PL element includes the *Orion* multi-purpose crew vehicle (MPCV) carrying 4 crewmembers, a single stage LLV carrying two 2.5 t PL pallets, plus a saddle truss that connects the forward PL element to the rest of the NLTV. At the end of the mission, the NLTV returns to Earth carrying the spent LLV and captures into a 24-hr elliptical Earth orbit (EEO) that has a lower $\Delta V$ requirement. In order to return to LEO, the NLTV's IMLEO would nearly double to ~347.8 t!

The first significant step in LDP production occurs when lunar outpost assets and $LLO_2$ production levels become sufficient to support a lunar surface-based LLV. By not having to transport a "wet" LLV to LLO on each flight, the NLTV now has a lower starting mass in LEO plus sufficient onboard propellant to return to a lower, higher energy EEO as shown in Figure 3b. As LDP production increases further and $LLO_2$ becomes available in LLO, from either a tanker LLV or from an evolving propellant depot, the NLTV's SNREs are outfitted with $LO_2$ feed systems and afterburner nozzles and the large in-line $LH_2$ tank is replaced by a smaller $LO_2$ tank (shown in Figure 3c). Using only Earth-supplied $LH_2$ but refueling with ~47 t of $LLO_2$, the NLTV is now able to return to LEO. Also because of optimized LANTR operation utilized during the round trip mission, the total engine burn time is cut in half as well.

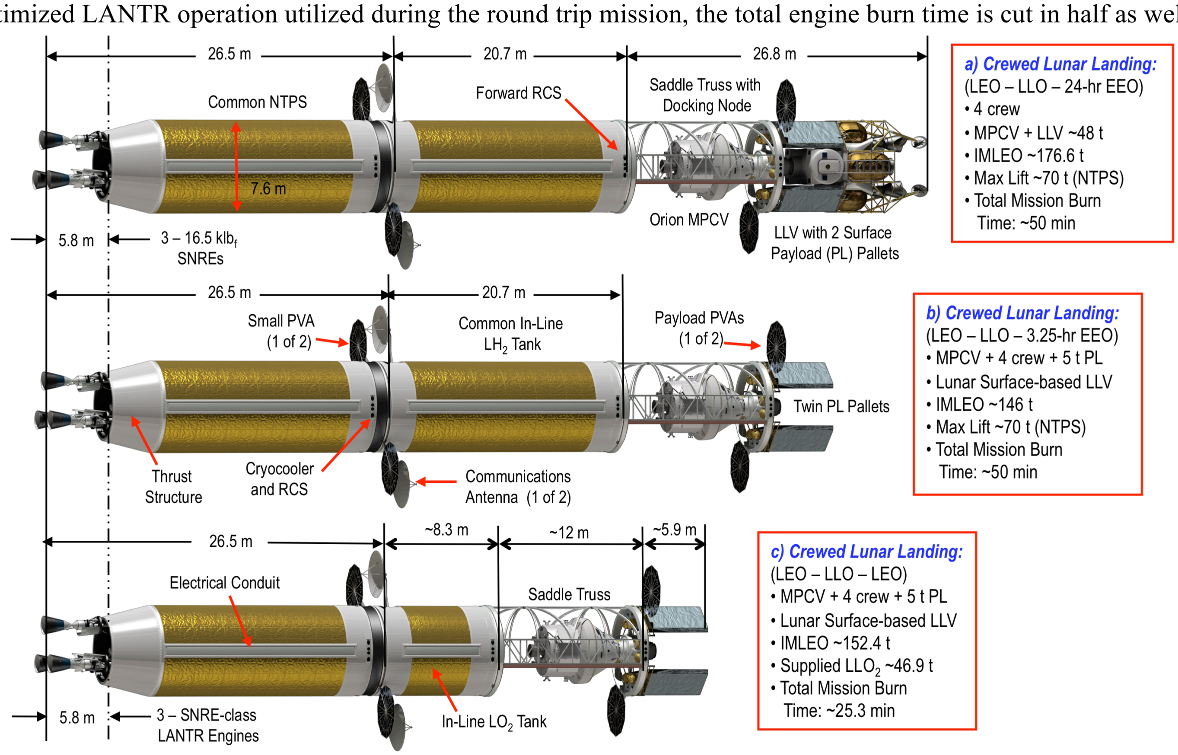


**FIGURE 3.** Variation in NLTV Size, IMLEO, Mission Capability and Engine Burn Time Resulting from the Development and Utilization of $LLO_2$ and the Transition to LANTR Operation

## GROWTH MISSION OPTIONS AND ASSOCIATED REFUELING NEEDS

Over time we envision the development of a totally space-based LTS with different types of NLTVs operating between transportation nodes located in LEO, LLO and LPO. One-way transit times to and from the Moon on the order of ~72 hours would be the norm initially. Eventually, however, as lunar outposts grow into permanent settlements staffed by visiting scientists, engineers and administrative personnel representing both government and private ventures, more frequent flights of shorter duration could become commonplace. To cut transit times between LEO and LLO in half to ~36 hours will require an ~25% increase in the mission's $\Delta V$ budget (from ~8 to 10 km/s) so versatile LANTR engines with adequate supplies of LDP for refueling will be key to ensuring LTVs of reasonable size. Examples of space-based LANTR LTV concepts discussed in this section are shown in Figure 4.

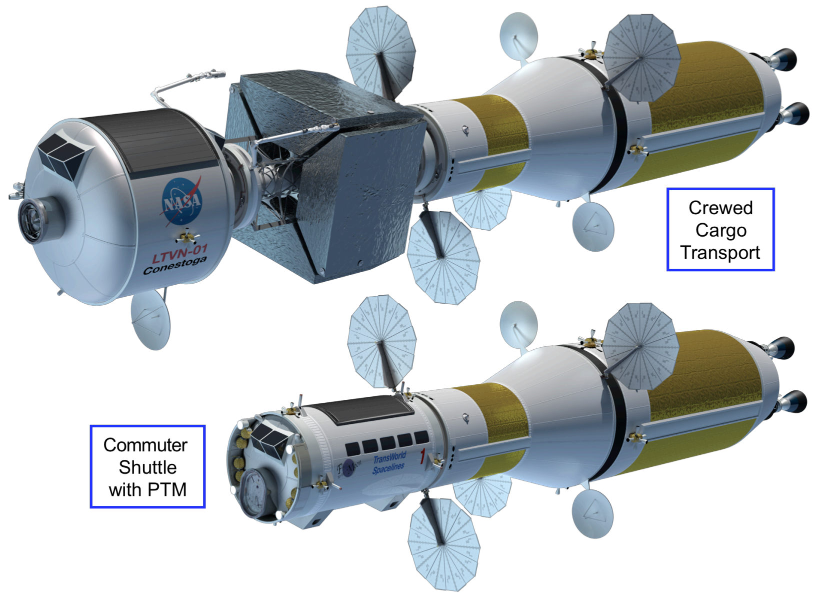


**FIGURE 4.** Space-based LANTR LTVs using a Common NTPS and Customized In-Line $LO_2$ Tank

Two different options for obtaining LDP are considered here. The first produces $LLO_2$ from abundant volcanic glass deposits located just north of the lunar "equatorial corridor" and the second both $LLO_2$ and $LLH_2$ from LPI deposits necessitating capture and departure from LPO. In Option 1, the LANTR LTVs use only Earth-supplied $LH_2$ ($ELH_2$) but refuel with $LLO_2$ for Earth return. Initially, the LANTR LTVs will transport $ELH_2$ to LLO for use by the LLVs and the hydrogen reduction processing plants producing the $LLO_2$. Later, once a propellant depot is established in LLO, it will be routinely supplied with $LLO_2$ transported from the surface using tanker LLVs. Similarly, dedicated NTR $LH_2$ tanker vehicles will supply the depot with ~25 t of $ELH_2$ on individual flights. In Option 2, it is assumed that tanker LLVs will transport $H_2O$ to a propellant depot in LPO where it will be electrolyzed and stored there for subsequent use. The LANTR LTVs operating out of LPO will refuel with $LLO_2$ primarily but will also be able to "top off" their NTP stages using the excess $LLH_2$ from the $H_2O$ electrolysis process for Earth return.

Table 2 provides a sampling of different missions, vehicle types, and trip times that have been examined along with the associated $LLO_2$ refueling requirements assuming volcanic glass and LPI as the source materials. All the cases shown use the same common NTPS described in the previous section and shown in Figures 3 and 4. Case 1, a crewed LTV mission, carrying the Orion MPCV and 5 t of cargo (shown in Figure 3c), uses an oversized in-line $LO_2$ tank consisting of two 7.6 m diameter ellipsoidal domes and requires ~47 t of $LLO_2$ for Earth return. Case 2 is a space-based crewed cargo transport (similar to that in Figure 4). It has its own dedicated habitat module weighing ~10 t, plus a 4-sided, concave star truss that has attached to it four 1.25 t PL pallets. The $LO_2$ tank is smaller and customized for this particular application resulting in a lower IMLEO and $LLO_2$ refueling requirement (~35 t).

Cases 3 and 4 show the impact on the crewed cargo transport mission of reducing the Earth-Moon transit times from 72 hours down to 48 and 36 hours, respectively. Because the $LH_2$ propellant loading in the NTPS is fixed at ~39.7 t for these missions, the LANTR engines run "$O_2$-rich" on the return leg (MR = 5, $I_{sp}$ ~516 s) so the $LLO_2$ refueling requirement for Case 4, with a 36-hour transit time, increases to ~71.6 t – more than double that needed for Case 2.

**TABLE 2.** LANTR Missions, Vehicle Types, and Refueling Needs Using Volcanic Glass and LPI

| Case Description * | Objective | Trajectory/Orbits ** | In-line $LO_2$ Tank | Results |
|---|---|---|---|---|
| 1. Crewed LANTR LTV with MPCV and 12 m saddle truss carrying 5 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 5 t cargo to LLO | 72 hour 1-way transit times; LEO – LLO – LEO $\Delta V$ ~7.984 km/s | 7.6 m OD x ~5.23 m L (~163.5 t $LO_2$) | IMLEO ~ 152.4 t; ~48.8 t $LO_2$ supplied in LEO; ~46.9 t $LLO_2$ refueling in LLO |
| 2. Crewed space-based LANTR LTV with 9.9 t hab module and 11 m star truss carrying 5 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 5 t cargo to LLO using alternative LTV configuration | 72 hour 1-way transit times; LEO – LLO – LEO $\Delta V$ ~7.996 km/s | 4.6 m OD x ~3.4 m L (~35.9 t $LO_2$) | IMLEO ~ 131.1 t; ~35.9 t $LO_2$ supplied in LEO; ~35.1 t $LLO_2$ refueling in LLO |
| 3. Crewed space-based LANTR LTV with 9.9 t hab module and 11 m star truss carrying 5 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 5 t cargo to LLO while also cutting transit times to 48 hrs | 48 hour 1-way transit times; LEO – LLO – LEO $\Delta V$ ~8.695 km/s | 4.6 m OD x ~4.1 m L (~48.0t $LO_2$) | IMLEO ~ 143.4 t; ~48.0 t $LO_2$ supplied in LEO; ~47.0 t $LLO_2$ refueling in LLO |
| 4. Crewed space-based LANTR LTV with 9.9 t hab module and 11 m star truss carrying 5 t cargo to LLO | Determine $LLO_2$ refueling needed to deliver 5 t cargo to LLO while also cutting transit times to 36 hrs | 36 hour 1-way transit times; LEO –- LLO – LEO $\Delta V$ ~9.838 km/s | 4.6 m OD x ~6.1 m L (~81.2 t $LO_2$) | IMLEO ~ 177.4 t; ~81.2 t $LO_2$ supplied in LEO; ~71.6 t $LLO_2$ refueling in LLO |
| 5. LANTR commuter shuttle carrying 15 t Passenger Transport Module (PTM) to LLO then back to LEO | Determine $LLO_2$ refueling needed to deliver the PTM to and from LLO with transit times of 36 hrs | 36 hour 1-way transit times; LEO – LLO – LEO $\Delta V$ ~9.835 km/s | 4.6 m OD x ~5.4 m L (~69.3 t $LO_2$) | IMLEO ~ 160.6 t; ~69.3 t $LO_2$ supplied in LEO; ~67.9 t $LLO_2$ refueling in LLO |
| 6. LANTR commuter shuttle carrying 15 t PTM to LPO then back to LEO | Determine $LLO_2$ refueling needed to deliver the PTM to and from LPO with transit times of 36 hrs | 36 hour 1-way transit times; LEO – LPO – LEO $\Delta V$ ~10.006 km/s | 4.6 m OD x ~6.0 m L (~80.0 t $LO_2$) | IMLEO ~ 172.5 t; ~80.0 t $LO_2$ supplied in LEO; ~72.1 t $LLO_2$ refueling in LLO |
| 7. LANTR commuter shuttle carrying 15 t PTM to LPO then back to LEO | Determine $LLO_2$ refueling needed to deliver the PTM to and from LPO; NTPS tops off with excess $LLH_2$ | 36 hour 1-way transit times; LEO – LPO – LEO $\Delta V$ ~10.047 km/s | 4.6 m OD x ~4.6 m L (~56.4 t $LO_2$) | IMLEO ~148.2 t; LTV refuels with ~55.3 t $LLO_2$ and NTPS tops off with ~6.9 t excess $LLH_2$ |
| 8. Rapid commuter shuttle carrying 15 t PTM to LPO then back to LEO | Determine feasibility of 24 hour transits using twin LANTR engines; NTPS tops off with excess $LLH_2$ | 24 hour 1-way transit times; LEO – LPO – LEO $\Delta V$ ~13.225 km/s | 4.6 m OD x ~8.3 m L (~116.6 t $LO_2$) | IMLEO ~204.3 t; LTV refuels with ~105.6 t $LLO_2$ and NTPS tops off with ~13.2 t excess $LLH_2$ |

* Cases 1 – 8 use a "Common $LH_2$ NTPS" (7.6 m D x ~15.7 m L); Propellant depots assumed in LEO, LLO and LPO; LANTR engines use optimized MRs
**LEO – 407 km, LLO – 300 km equatorial, LPO – 300 km polar orbit; Total round trip mission $\Delta V$ values shown include g-losses

The use of LANTR engines and LDPs could also enable the development of a commercial "commuter shuttle" service with 1-way trip times to and from the Moon ranging from 36 to 24 hours. The LANTR commuter shuttle (shown in Figure 4) carries a forward Passenger Transport Module (PTM) that contains its own life support, power, instrumentation and control, and reaction control system. It provides the "brains" for the LANTR-powered shuttle which is home to the 18 passengers and 2 crew members while on route to the Moon [12]. Arriving in LLO, the PTM detaches and docks with a waiting "Sikorsky-style" LLV that delivers it to the lunar surface. From here the PTM is lowered to a "flat-bed" surface vehicle for transport over to the lunar base and passenger unloading.

Case 5 is a commuter shuttle LTV that carries a 15 t PTM to LLO and back, has 36-hour 1-way trip times, and uses only $ELH_2$. It has an IMLEO of ~161 t and refuels with ~68 t of $LLO_2$. Case 6 is similar to Case 5 but operates between LEO and LPO. Because of the higher $\Delta V$ budget needed to access LPO, the shuttle's IMLEO and $LLO_2$ refueling requirements are larger at ~173 t and ~72 t, respectively. The total burn time on the LANTR engines for the round trip mission is ~25.3 minutes. Also, with the engines running $O_2$-rich and producing ~170.3 $klb_f$ of total thrust, the g-loading on the passengers during the final EOC burn varies from ~0.75 to ~1.5g.

Case 7 shows the benefit of utilizing the excess $LLH_2$ produced from the depot's $H_2O$ electrolysis process to top off the NTPS' $LH_2$ tank. By supplying the commuter shuttle with just under 7 t of $LLH_2$, $LLO_2$ refueling decreases by ~17 t and the shuttle's IMLEO decreases by more than 24 t. By switching to a "twin engine" NTPS, and again topping off with ~13 t of excess $LLH_2$, 24-hour 1-way transit times are also possible as shown in Case 8. This rapid shuttle capability comes at the expense of increased mission $\Delta V$ (~13.2 km/s), IMLEO (~204 t) and $LLO_2$ refueling (just under 106 t), but the passenger g-loading during the EOC burn is more manageable varying from ~0.5 to ~1g.

## SUMMARY AND CONLUSIONS

The NTR offers significant benefits for lunar missions and can take advantage of the leverage provided from using LDPs – when they become available – by transitioning to LANTR propulsion. This enhanced version of NTP

provides a variable thrust and $I_{sp}$ capability, shortens burn times, extends engine life, and allows combined $LH_2$ and $LO_2$ operation. Its use together with adequate supplies of LDP for refueling can lead to a robust nuclear LTS with unique mission capabilities that include short transit time crewed cargo transports and commuter shuttles.

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